

EFFECTS OF DISTURBANCE ON NITROGEN EXPORT FROM FORESTED LANDS OF THE CHESAPEAKE BAY WATERSHED

KEITH N. ESHLEMAN¹, ROBERT H. GARDNER¹, STEVEN W. SEAGLE¹,
NANCY M. CASTRO¹, DANIEL A. FISCUS¹, JAMES R. WEBB², JAMES N.
GALLOWAY², FRANK A. DEVINEY² and ALAN T. HERLIHY³

¹*Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, MD 21532 USA;* ²*Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903 USA;* ³*Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97333 USA*

Abstract. The objective of this research project is to develop, test, validate, and demonstrate an analytical framework for assessing regional-scale forest disturbance in the mid-Atlantic region by linking forest disturbance and forest nitrogen export to surface waters at multiple spatial scales. It is hypothesized that excessive nitrogen (N) leakage (export) from forested watersheds is a potentially useful, integrative "indicator" of a negative change in forest function which occurs in synchrony with changes in forest structure and species composition. Our research focuses mainly on forest disturbance associated with recent defoliations by the gypsy moth larva (*Lymantria dispar*) at spatial scales ranging from small watersheds to the entire Chesapeake Bay watershed. An approach for assessing the magnitude of forest disturbance and its impact on surface water quality will be based on an empirical model relating forest N leakage and gypsy moth defoliation that will be calibrated using data from 25 intensively-monitored forested watersheds in the region and tested using data from more than 60 other forested watersheds in Virginia. Ultimately, the model will be extended to the region using spatially-extensive data describing: 1) the spatial distribution of dominant forest types in the mid-Atlantic region based on both remote sensing imagery and plot-scale vegetation data; 2) the spatial pattern of gypsy moth defoliation of forested areas from aerial mapping; and 3) measurements of dissolved N concentrations in streams from synoptic water quality surveys.

1. Introduction

Forests are the dominant land cover type in the mid-Atlantic region of the United States, despite a long history of intensive logging and clearing of the land for settlement and agriculture before the 20th century and a more recent decline in forest cover due to urban and suburban development (Gardner et al. 1996). Presently, it is estimated by the U.S. Environmental Protection Agency that the Chesapeake Bay watershed is composed of 60% forest, 29% agriculture, and 10% urban land. The forested lands of the Chesapeake watershed and of the entire mid-Atlantic region are an important natural and economic resource, providing fiber for building materials, paper, and fuel; habitat for wildlife and endangered floral and faunal species; and recreational opportunities for human inhabitants of the area. As importantly, due to their close coupling with the regional hydrological cycle, forested lands provide important economic benefits to the region in the form of water supplies for domestic, industrial, and consumptive uses. Relative to other land uses, surface

and ground water supplies produced by forested lands are typically found to be of higher quality, although various negative effects of forest management practices on water quality have been documented since experimental manipulations of watersheds were first conducted during the early 1960s (e.g., Douglas and Swank 1975, Bormann and Likens 1979).

Several recent papers have also demonstrated surface water quality impacts associated with forest defoliations by the gypsy moth larva (*Lymantria dispar*). Using 13 years of discharge and streamwater chemistry data from White Oak Run in Shenandoah National Park, Virginia, Webb et al. (1995) showed that streamwater changes following defoliation included increasing concentrations of nitrate, strong base cations, and hydrogen ion, with decreasing concentrations of acid neutralizing capacity (ANC) and sulfate; Eshleman et al. (1995) showed that the intensity of episodic acidification increased at White Oak Run following the initial defoliation, primarily due to the transient leakage of nitric acid from the watershed during stormflow events. Both studies thus confirmed that non-harvesting forest disturbances can significantly affect rates of loss of solutes to streamwater, which is consistent with stream responses following both experimental and natural forest disturbances at the Coweeta Hydrologic Laboratory in North Carolina reported earlier (Swank 1988). Eshleman et al. (1998) documented the synchronic leakage of dissolved nitrogen (N) from five gaged forested watersheds in the mid-Atlantic region during the early 1990s and showed that the leakage occurred contemporaneously with an outbreak of gypsy moth defoliation; peak annual N losses from the five watersheds were 2–3 orders of magnitude higher than the pre-defoliation values and ranged from 69–350 eq/ha-yr, greatly exceeding the losses computed by Swank (1988) for the Coweeta watershed (32 eq/ha-yr).

2. Objectives and Hypotheses

The objective of this research project is to develop, test, validate, and demonstrate an analytical framework for assessing regional-scale forest disturbance in the mid-Atlantic region by linking forest disturbance and forest N export to surface waters at multiple spatial scales. It is hypothesized that excessive N leakage (export) from forested watersheds is a potentially useful, integrative “indicator” of a negative change in forest function which occurs in synchrony with changes in forest structure and species composition (Hunsaker and Carpenter 1990). The research focuses on forest disturbance associated with recent watershed defoliation by the gypsy moth larva at spatial scales ranging from small watersheds to the entire region. It is expected that the overall approach—while focused on gypsy moth defoliation of forests—is also applicable to other forest disturbances which produce N export to surface waters (e.g., logging) and perhaps to other terrestrial systems (e.g., agricultural disturbances). The project will also provide quantitative estimates of annual regional export of dissolved N from forested lands to major

drainage basins (including Chesapeake Bay) in the region. These estimates will clearly benefit and complement larger, more comprehensive modeling efforts currently underway in the mid-Atlantic region, particularly those associated with the goal of the Chesapeake Bay Agreement of 1987 to reduce by 40% the nutrient loadings to Chesapeake Bay by the year 2000 (Linker et al. 1996, Bicknell et al. 1993, Chesapeake Executive Council 1989). Three research hypotheses are currently being tested:

- Nitrogen export from forested watersheds in the mid-Atlantic region is primarily attributable to forest disturbances, operating at both the local- and regional-scales. These disturbances produce a biogeochemical signal that is a robust, integrative indicator of forest “health”—one that can be described using a well-known linear response model. Local disturbances such as logging are significant, but recent watershed defoliation by the gypsy moth larva is the primary disturbance operating regionally. Further, disturbance-induced N leakage from forests overrides multiple other factors such as forest age, land-use history, soil type, N deposition loading, and runoff rate.
- Changes in forest species composition in the mid-Atlantic region—such as declines in dominance of oak species and increases in shade-tolerant species—have been induced or exacerbated by gypsy moth defoliation. Therefore, regional patterns and timing of shifts in species dominance and succession should be well-correlated with spatial patterns of gypsy moth outbreaks. However, the low frequency (once every 10 years) with which forest composition in the region is currently measured may limit the applicability of these changes as quantitative indicators of forest health at the landscape scale.
- If both N export and rapid forest succession are largely disturbance-induced by gypsy moth defoliation in the region, then broad-scale patterns of dissolved N leakage, forest succession, and forest disturbance should be highly correlated, both spatially and temporally.

3. Technical Approach

The technical approach for linking forest disturbance and N leakage to surface waters makes use of extensive forest, forest disturbance, and water quality data collected for the mid-Atlantic region at a variety of spatial scales (intensive sites, subregional survey, regional survey, and remotely sensed data). The critical data sets being synthesized are:

- annual N fluxes from approximately 25 small ($<15 \text{ km}^2$), intensively-monitored forested watersheds in the region (many cited by DeWalle and Pionke 1994);

- surface water N concentration data for subregional stream populations such as Virginia trout streams (Webb et al. 1994);
- regional Forest Inventory & Analysis (FIA) plot data, collected for all states in the region (Hansen et al. 1997);
- regional gypsy moth defoliation data for all states in the region (Liebhold and Elkinton 1989);
- regional surface water N concentration data, such as from the National Stream Survey (NSS, Kaufmann et al. 1991) and the Environmental Monitoring and Assessment Program (EMAP, Paulsen et al. 1991);
- thematic mapper (TM) imagery from NASA's Landsat satellites.

There are five carefully-linked tasks associated with our overall research objective that will allow us to test the hypotheses. These tasks are described below.

Task 1: *Characterizing forest composition, recent disturbance history, and annual N export for intensively-monitored watersheds.* The objective of this task is to assemble a data base for testing the hypothesis that N leakage from individual forested watersheds in the mid-Atlantic region can be attributed to recent forest defoliations by the gypsy moth larva. Annual N leakage data for a large sample of small, intensively-studied watersheds was recently reported by DeWalle and Pionke (1994); we are making use of the same data base, but have updated it with more recent information and data from other sites wherever possible. Gypsy moth defoliation history is based on digital maps of annual statewide defoliation derived from aerial sketch mapping, in some cases augmented with color infrared photography. Forest species composition of these watersheds is being estimated using ground plot-level vegetation surveys; the Bitterlich variable plot method is used to estimate basal area by species of all living and dead overstory trees (Lindsey et al. 1958). An important measurement obtained from the inventory is the percentage of basal area in oaks, since defoliation potential of the gypsy moth is largely predicted by the dominance of oak species (Gansner et al. 1993). Data obtained under this task will be used in applying an empirical regional model of N leakage.

Task 2: *Modeling N export from intensively-monitored watersheds due to disturbance.* We propose that annual N export from forested watersheds to surface waters resulting from a single forest disturbance can be described using a linear impulse response function model and that N export from multiple forest disturbances in time can thus be described using the convolution integral. For example, for a response to gypsy moth defoliation, we expect the convolution integral to take the following form:

$$N_w(t) = \int_0^t U(t-\tau)D_w(\tau)d\tau + B_w \quad (1)$$

where: $N_w(t)$ is the nitrogen export response for watershed w , $U(t - \tau)$ is a unit N export response function (UNERF), $D_w(\tau)$ is the proportion of forested watershed disturbed (defoliated) at time τ ($0 < D_w(\tau) < 1$); and B_w is the baseline N export from watershed w in the absence of defoliation. The use of this linear UNERF model is (a) analogous to the use of the unit hydrograph model for predicting stormflow responses of watersheds; (b) based on the solution of the differential equations representing the operation of a linear system; and (c) follows two basic principles: the principle of proportionality and the principle of superposition (Chow et al. 1988). Actual N export time series for disturbed watersheds have the same general shape that is characterized by a steep increase in export beginning at the time of disturbance, a peak export rate that occurs within a few years following disturbance, and a recession to normal baseline export levels over several years following the peak (Figure 1).

We also hypothesize that UNERF's and baseline N export rates for intensively-studied forested watersheds can be identified by deconvolution of the time series of annual N export, given knowledge of the timing and magnitude of forest disturbance (defoliation) within each watershed during the period of data collection. This is completely analogous to the determination of a unit hydrograph from actual storm hydrographs for known rainstorm events. Deconvolution of responses for multiple disturbances is more difficult than for single disturbances, because of the possibility of errors or important non-linearities (Chow et al. 1988). Deconvolution can be accomplished by matrix algebra or linear regression, but the preferred method is linear programming. By this technique,

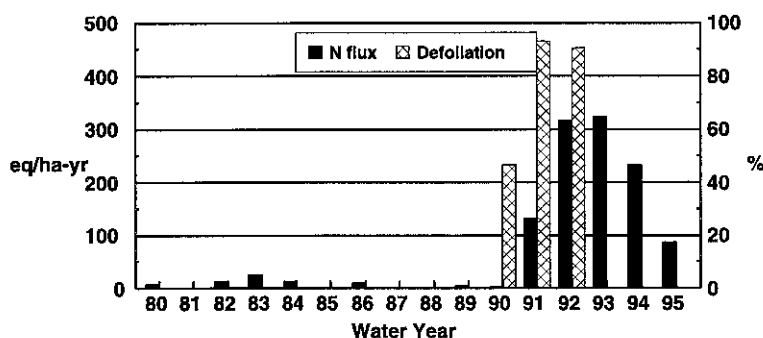


Figure 1. Annual dissolved N export and watershed defoliation by the gypsy moth larva for White Oak Run, Shenandoah National Park (Virginia) for water years 1980-1995. Gypsy moth defoliation is expressed as a percentage of the watershed defoliated based on aerial sketch maps.

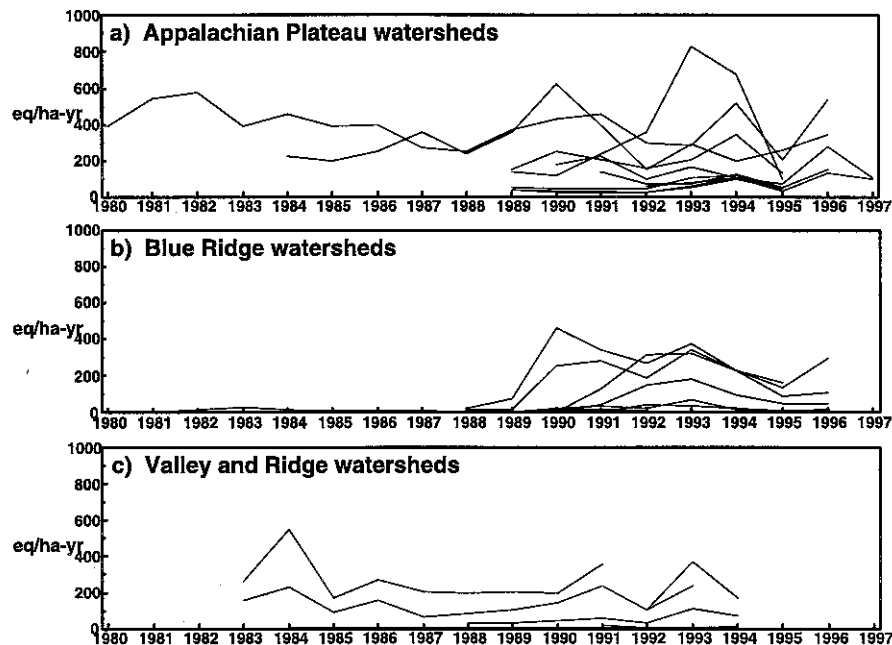


Figure 2. Annual dissolved N export for 23 intensively-monitored forested watersheds in three physiographic provinces of the mid-Atlantic region during the period from 1980-1997.

the solution is formulated as an objective function which minimizes the absolute error between measured and predicted values of $N_w(t)$ (Chow et al. 1988). Deconvolution of annual surface water N export time series for approximately 25 forested watersheds in the region is being performed using linear programming, making use of recent disturbance histories based on state defoliation maps (e.g., Liebhold and Elkinton 1989). We expect that either one universal UNERF will be obtainable for the entire mid-Atlantic region or unique UNERF's will be identifiable for specific physiographic provinces or ecoregions.

Task 3: Verification of N export as an indicator of disturbance at subregional scales. Testing of the UNERF model will be performed by comparing predictions and measurements of N export for at least one subregional data set not examined in Task 2. We expect to use the Virginia Trout Stream Sensitivity Survey (VTSSS; Webb et al. 1994) data base containing quarterly dissolved N data for approximately 65–80 streams in western Virginia. We will need to make some assumptions about the relationship between quarterly or spring “index” composition and annual discharge-weighted concentrations and an-

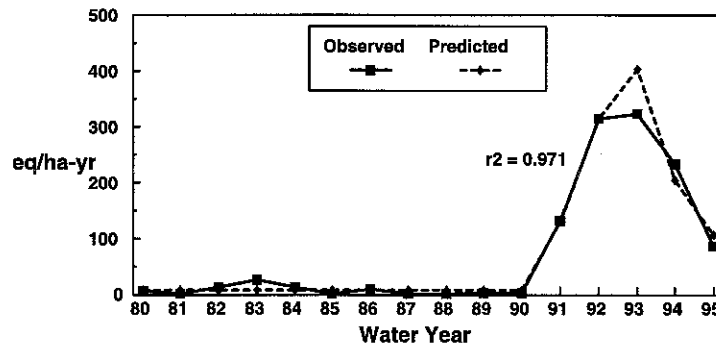


Figure 3. Comparison of observed annual dissolved N fluxes from White Oak Run, Virginia with predicted annual N fluxes using the UNERF model.

nual N fluxes, but we are aware of two recent studies that show that annual N export can be reliably computed from quarterly streamwater composition as long as discharge can be accurately estimated (Dow 1992, Eshleman et al. 1998). Several statistical tests will be employed to verify the model for individual watersheds (e.g., linear regression of observed vs. measured N export values). Since previous regional model applications have demonstrated the utility of comparing statistical distributions rather than values for single sites (Small and Sutton 1986, Hornberger et al. 1987, Church et al. 1989), we will take correspondence between the predicted and observed moments (mean, variance, and skew) of the regional distribution of N export as a better measure of modeling success.

Task 4: Scaling forest point data to landscape scales. The first objective of this task is to use intensive data describing species composition of forested lands to create a fine-grained, statistically reliable, and spatially-extensive data set describing the location and distribution of forest types within the region. Specifically, FIA data (Hansen et al. 1997) characterizing forest species composition of individual forest plots will be used to predict composition of all forested land within the Chesapeake Bay watershed. Our classification results will be validated using field data on forest composition collected in a subsample of the classified watersheds. This scaling of FIA data will allow us to examine forest composition as another explanatory variable for N export from these watersheds.

Our approach to scaling forest composition both contrasts with and complements forest classification using satellite imagery. The Anderson level II classification of currently available imagery does not resolve species differences which we believe are critical for estimating relationships among forest disturbance and the spatio-temporal patterns of N export to surface waters. In

contrast, the FIA forest data provide a high resolution description (i.e., species composition) of forest types that we suggest can be used to directly predict the forest type of unmeasured stands with significant accuracy. Regionally-distributed field validation data can also be used as independent data to facilitate Anderson Level III classification (forest composition types) based on satellite imagery.

Our second objective for this task is to describe trends in forest composition over the region. We will use FIA data from the last two inventories within each state to calculate a “change index” for forest composition. Collectively, these point estimates of forest trajectories will describe spatial trends in forest succession across the region and will be correlated with gypsy moth disturbance to examine the role of disturbance in inducing changes in forest composition.

Task 5: *Correlating spatial and temporal patterns of N export and forest species composition changes with forest disturbance at the regional scale.* The purpose of this task is to determine landscape-scale relationships between forest type, forest disturbance, forest composition changes, and N export in the mid-Atlantic region. The task will be completed within a linked geographic information system (GIS) modeling framework, making use of these key data layers described under previous tasks. The key inputs to the parameterized UNERF models will be the regional distribution and timing of gypsy moth defoliation based on annual maps. Annual N export will be predicted as a function of these input variables, producing another data layer to overlay against maps of forest composition and forest composition change. Spatial variation in values of the change index and rate of change will be compared to historical patterns of gypsy moth disturbance to infer effects of disturbance on forest composition trajectories.

The task involving N export would be considered strictly correlative, were it not for the possibility of validating these predictions from the GIS-linked UNERF model using regional synoptic stream chemistry data from the NSS and EMAP programs. Since both surveys sample a definable target population of stream reaches draining watersheds in the mid-Atlantic region, were conducted during the period of interest (mid 1980s through present), and provide periodic data for assessing both temporal and spatial variations in N concentrations in streamwater in the region, we will use the UNERF model to predict a time series of annual N export from a sample of these watersheds that represents the “forested watershed stratum”. We propose that the distribution of spring baseflow concentrations from the NSS and EMAP data bases can be used to approximate discharge-weighted annual concentrations of nitrate-N in each stream—after the data are stratified to isolate the subpopulation of streams draining only forested land. We will analytically compare actual cumulative frequency distributions (CDF’s) for each

ecoregion and for the Chesapeake Bay watershed as a whole with predicted CDF's for each region for each year, in addition to examining correlations for individual watersheds. Finally, the annual export of N from forested lands to Chesapeake Bay will be obtained by spatial integration of the annual N flux over all forested lands in the Chesapeake Bay watershed. This export would be computed for each year for which gypsy moth defoliation and deforestation data are available for the region. A spatially-averaged, annual N export will also be obtained by dividing the annual export values by the area of forested land within the watershed.

4. Preliminary Results

4.1 TASK 1

To date, our research has focused primarily on characterizing the intensive watersheds in the region and on parameterizing the UNERF model. Dissolved streamwater N (NO_3^-) concentration data and daily stream discharge data were obtained for 25 intensively-monitored watersheds in the region. Combining these two data sets using the linear interpolation method of Eshleman et al. (1998), monthly and annual N fluxes (per area basis) were computed for 23 of these watersheds: 10 watersheds in the Appalachian Plateau, 7 watersheds in the Blue Ridge, and 6 watersheds in the Valley and Ridge physiographic province. Figure 2 illustrates both the temporal and spatial variability of annual N fluxes among watersheds in the region. Of the three regions shown, data for the Blue Ridge watersheds appear most consistent with the hypothesis that gypsy moth defoliation in the late 1980s and early 1990s is a primary cause of N leakage from forested watersheds. Defoliation histories for the watersheds are currently being obtained from state and federal forest management agencies. In addition, forest composition plots have already been surveyed in 16 of the 25 intensively-monitored watersheds.

4.2 TASK 2

To demonstrate the utility of the UNERF model (Equation 1), data from the White Oak Run watershed (Figure 1) were used to calibrate the model. To simplify the linear programming problem, it was assumed that the annual N flux reaches a peak in the water year following defoliation and declines exponentially thereafter; a first-order decay constant of 0.7 yr^{-1} was assumed. Visual comparison of the observed data with the model predictions suggest excellent agreement (Figure 3).

Further, a linear regression of the observations on the predictions was found to be statistically significant ($\alpha = .05$) and virtually unbiased. Eshleman (in review) has discussed the general overall applicability of this empirical linear methodol-

ogy for forested watersheds subjected to both natural and anthropic disturbances. Using the disturbance and N export data from the 23 watersheds, we are currently parameterizing the UNERF model and examining the extent to which model parameters can be predicted on the basis of forest composition. Once this task is completed, our next step will be to evaluate the extent to which a general or "regional" UNERF model can explain the variations in N export among watersheds in the region.

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